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A potential candidate for the sustainable and reliable domestic energy generation–Thermoelectric cogeneration system

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ABSTRACT

Due to being solid-state, noiseless and maintenance free, thermoelectric devices have found wide applications in different areas since they were discovered over 180 years ago. The applications are concerned with environment-friendly refrigeration and power generation in transportation tools, industrial utilities, military devices, medical services and space applications. It is utilisation of waste heat in varying applications that make the modules particularly attractive. Nevertheless, despite a few academic papers, there has not been extensive use in the domestic sector. A concept of thermoelectric cogeneration system ('TCS') is proposed to highlight the direction for enhancing the sustainability by improving the energy efficiency in domestic sector. Compared to the thermoelectric systems used in other areas which only uses the part of converted energy but wastes the unconverted part by dissipating it into the environment, the system presented here maximally recover the available heat by generating electrical power and producing hot water simultaneously. The viability of this system concept is evaluated on a bench-scale experimental prototype. The outputs of electrical power and hot water have been investigated at different temperature difference. The cost saving potential and cost recovery period have been estimated using the available heat sources in domestic sector. The results intend to provide reference for developing the real-scale domestic thermoelectric cogeneration system and show the potential benefits.

1. Introduction

Power generation using thermoelectric generators have been utilised in the areas like aerospace facilities, transport tools and industry utilities, in which a considerable amount of waste heat offers a great opportunity for making direct use. Fig. 1 shows the energy consumption in four major sectors [1], where a considerable amount of energy has been exhausted into environment without being used.

In vehicles, over 50% of the total fuel energy escapes to the ambient environment as heat loss through the exhaust system and radiator. The possibility of recovering it with thermoelectric module was explored as early as in 1914 [2]. Joint efforts by academia and industry used the most advanced available thermoelectric materials of the time to achieve an overall efficiency of 5–10% [3]. Due to the different temperature levels across the section between engine and exhaust, the optimum performance could be obtained by adapting specific modules for individual temperature level and applying segmented materials or multistage designs. Meanwhile, thermoelectric devices are also used to control temperature and produce cooling and heating from electrical power input in automobiles. This type of application avoids the use of environmentally harmful refrigerants.

Explorations in hostile and inaccessible locations, advances in medical physics, deployment of marine and terrestrial surveillance systems and earth resources require autonomous long-life sources of electrical power. Thermoelectric generators have more than 100,000-h steady-state operation and precise temperature control [4]. Their developments were used by NASA to provide electrical power for spacecraft since 1961. The reliability of thermoelectric technology has been demonstrated in the Voyager spacecraft with Voyager 1 passing into the Heliosheath about 8.3 billion miles from Earth on May 24th 2006. The application normally involves using radioisotopes as the heat sources which are restricted in specialised applications where the advanced properties outweigh the low conversion efficiency. Early successful space applications of thermoelectric power generation were achieved by the development of systems for Nuclear Auxiliary Power in America in 1955 [5]. Similar

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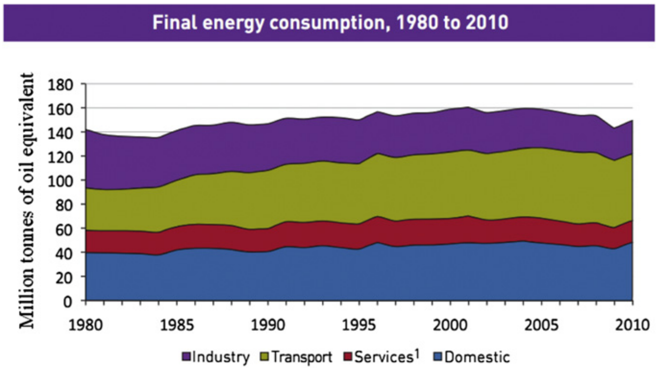

Fig. 1. Energy consumption of different sectors in the UK (1980–2010).

applications on artificial satellites Cosmos-84 and Cosmos-90 in USSR were also recorded [6]. For the aircraft industry (both commercial and military), thermoelectric devices can capture waste heat from the engine and operate over the entire aircraft flight envelope without affecting engine's performance.

The process industries include food, beverages, chemicals, pharmaceuticals, petroleum, ceramics, base metals, coal, plastics, rubber, textiles, tobacco, wood and wood products, paper and paper products. Industrial energy consumption represents a large contingent of energy consumption. For example, it accounted for more than a fifth of all UK energy consumption in 2001 consuming 35,152 thousand tonnes of oil equivalent [7], as shown in Fig. 1. Due to the large scale in most cases, industries involve with a huge amount of energy consumption, in which a considerable amount escapes to the environment in the form of exhausting, radiation and cooling. Fig. 2 compares the energy use and loss in energy systems across sixteen industrial sectors. Five industrial sectors, which include petroleum refining, chemicals, forest products, iron and steel, and food and beverage, account for over 80% of all the energy inputs to energy systems. They are large users of steam systems and fired systems such as furnaces and dryers. In total, energy losses associated with energy systems in these five industries totals represents over 15% of the energy consumed by U.S. industry.

This energy loss or waste heat, produced in the processes of fuel combustions and chemical reactions, is wasted by ending up in the environment rather in the product due to unnecessary processes, intensive drying, inefficient boilers and steam systems. The possibility of employing thermoelectric technology to generate electrical power from low temperature (80–100 K) heat source on off-shore oil platforms was discussed in 1992 [9]. Applications in both small scale and large scale for recovering heat from combustible solid waste have been developed in Japan [10]. An estimated conversion efficiency of 4.36% was achieved in a small scale onsite experiment

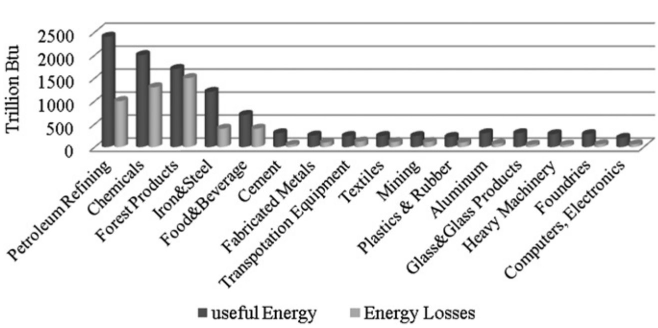

Fig. 2. Energy consumption chart in different industrial sectors [8].

using a 60 W thermoelectric module installed near the boiler section of an incinerator plant [11].

Nowadays, the use of PV (photovoltaic) technology takes over the major role of domestic power generation in many countries and regions. It has to be mentioned that PV delivers higher conversion efficiency compared to the thermoelectric generator. However, it has a small capacity factor due to its dependence on solar radiation. The disadvantage of PV is obvious especially in the regions that show a lack of solar radiation. Due to multi-heat-sourcing, quiet, long period reliable and maintenance free operation, thermoelectric generators have become an environmentally friendly and energy saving star despite lower efficiency compared to solar PV power generation. Efforts have been continuously made to adopt thermoelectric technologies in many different areas. Relevant investigations have been carried out in the pursuit of optimum and sustainable ways of using them.

The domestic power generation using thermoelectric technology has been mentioned in previous studies [12–15]. However, the common disadvantage shown by these stove application designs lies in the use of a cooling fan which consumes electricity and has moving parts. Most of heat output is exhausted to the environment in an unorganised way except for [15] which uses the heat for space/water heating; only a small part of the absorbed heat is converted into electricity. This disadvantage is enlarged further when the conversion efficiency is low. This paper introduces a concept of domestic TCS on a bench-scale experimental prototype which overcomes low system efficiency of current domestic application designs and is oriented to be integrated to existing domestic boiler systems. The power output and heat output have been investigated under different temperature differentials. The viability of the real-scale domestic TCS has been analyzed and prospected based on the experimental results. The annual cost saving and cost recovery period has been estimated on the basis of available heat sources in domestic environment. One of the intentions is to provide information to decision makers, technical managers and house owners for assessing the possible impact of integrating this technology to the domestic sector in future.

2. Design for domestic application

2.1. Background

Thermoelectric materials can be used for either cooling or power generation. Its construction consists of arrays of N & P type semiconductors in which, by applying a heat source on one side and a cooling heat sink to the other side, electric power is produced and vice versa. As shown in Fig. 3, when a temperature difference is established between two ends of semiconductor element, a voltage is generated. This effect, discovered by Thomas J. Seebeck, is called Seebeck effect.

The thermoelectric properties of thermoelectric materials, which form the semiconductor element, are characterized by the dimensionless figure of merit ZT, which is defined in terms of intrinsic material properties of both the N-and P- type materials and determined by three physical properties—Seebeck coefficient (S), electrical conductivity (σ), and thermal conductivity (λ). It can be related to the physical properties by Eq. (1):

$$ZT = \sigma S^2 T/\lambda \tag{1}$$

The larger the value of ZT, the better thermoelectric performance the material has. The materials with higher σ and lower λ have larger value of Z, which contributes more to the enhancement of η. It characterizes the capability of thermoelectric generator in converting heat into electricity and is given by Eq. (2):

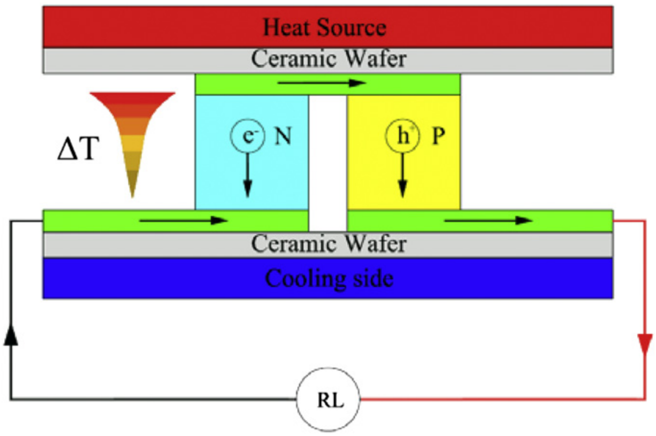

Fig. 3. Schematic diagram of thermoelectric generation.

$$\eta = \frac{\Delta T}{T_h}\left(\frac{\sqrt{Z\overline{T}+1}-1}{\sqrt{Z\overline{T}+1}+1-\Delta T/T_h}\right) \tag{2}$$

Despite the current low conversion efficiency of around 3–10% when used as power generators, they are strongly advantageous as they have no moving parts and are therefore both more reliable and durable compared to conventional energy technologies. Apart from that, they are scalable without releasing any pollutant to the environment during the operations. Hence, they would be ideal for applications in many areas at different scales replacing the traditional cooling and power generation methods.

In the domestic environment, almost all types of heat resources, such as boiler, wood/diesel/biomass burning stove or other available heating facilities, are eligible for energy conversion. The efficiency of the facilities could be improved by producing extra electrical power and thermal energy using the unused heat. Thermoelectric generator can also be used as the parasitic generator. An example was given by its application in a domestic central heating system where the modules were located between the heat source and the water jacket [16]. It converts about 5% of heat output from the gas/oil burner into electrical power before the heat output reaches the central heat exchanger and the remained 95% is transferred to the heat exchanger for space heating in the house. This paper intends to show the possible benefit of recovering the available free/low-cost heat source by employing the TCS concept in the domestic environment. The benefit is estimated in a case study which takes solar power and boiler waste heat into account based on the results of an experimental study conducted in the lab environment. The practical details about system design and construction are not introduced in this paper considering the large amount of content it would involve.

2.2. Case study

2.2.1. Available heat source

For residual spaces, apart from the solar radiation which is a common heat source in the domestic environment, one of other main available heat sources is the boiler waste heat. Domestic boiler is a common heating facility which has been widely used in the UK. Good understanding of the availabilities of these heat resources enables us to unveil the potential and benefit of applying TCS in domestic sector. In order to fully understand the availability of solar power, a comprehensive study conducted on the solar energy arriving at the surface of the Earth has been carried out by the Institute for Environment and Sustainability of European Commission [17]. The relevant results are cited to show the solar availability in different regions and countries. The amount of available solar energy depends on the geographical variability, weather conditions and time dynamics. The geographical analysis of the availability helps us understand the contribution that TCS could make to the improvement of domestic power conditions. Taking the UK as an example, supposing the modules are mounted at the optimum angle, the yearly sum of generated electricity per area in the UK is 820 kW h/kW$_p$. For a 1/kW$_p$ peak power, the required area of solar PV is 6.7 m^2 on the assumption of 150 W/m^2 power density. Hence, the equivalent yearly sum of absorbed direct solar radiation is 122.4 kW h/m^2.

Domestic power consumption in the United Kingdom between 1970 and 2000 has been studied and given by National Statistics from DTI in the UK [7]. It showed that energy consumed on space and water heating represents 82% of energy used in households. The domestic boiler plays the major role of space/water heating by burning gas (oil in some cases). It heats water up to the required temperature level before it goes to the central heating system and hot water user ends. However, not all the heat produced from burning the fuel is effectively used. A considerable amount of fuel energy is exhausted into environment without being used. The amount is determined by the boiler efficiency which generally lies between 55% and 90% [18].

The temperature of exhaust gas varies in the range of 80–130 °C for new boilers with the efficiency at nominal 90%. It is even higher for the used boilers whose efficiency degrades with the used period. Generally, the waste heat exhausted from domestic boilers depends on the boiler efficiency which varies with the manufacturers, specifications and used period. The nominal efficiency of new boilers is no more than 90%. Here a boiler with efficiency of 80% is taken as an example to estimate the total waste heat exhausted by one domestic boiler in 2009 in the UK, shown in Table 1. The annual waste heat per boiler is 3076.8 kW h.

2.2.2. Material match

According to operating temperature, thermoelectric materials are classified into three categories: low temperature, intermediate temperature and high temperature. The low temperature type, which includes alloys based on bismuth in combinations with antimony, tellurium or selenium, utilises general waste heat or heat from warm/hot water by operating up to 523 K, while the latter two which include the alloys of lead telluride and silicon germanium are oriented for incineration/steel plants and automobile exhaust, respectively. Their operating temperatures can reach up to 850 K and 1300 K. The application of high temperature type means higher cost. Suitable application of thermoelectric material is generally referred to large electrical power factor, good cost effectiveness and being environmentally friendly. For high operating temperature, modules with segmented thermoelectric elements have larger average ZT over a large temperature drop compared to those using same alloy in the element. The thermoelectric efficiency reached as high as 20% operating between 300 K and 975 K [20]. However, for the domestic power environment considered in this paper (under 473 K), Bi_2Te_3, the most successful commercialized thermoelectric materials with the optimum ZT (0.98) in the low range of 353–413 K, ought to have a better performance and lower cost due to a good figure of merit in operating temperature range available in the domestic environment.

2.2.3. Domestic application

Considering the current low conversion efficiency of thermoelectric module, it is uneconomical to build up a heat source just for thermoelectric power generation because the length of the cost recovery period is unforeseeable. A rewarding concept would be

parasitizing in other facilities which exhaust a considerable amount of unused heat, or combining the solar power. These facilities include the boiler, wood burning stove, fireplace and any other heating devices. The advantage of those heat sources is the free/low-cost use which outweighs the disadvantage of low conversion efficiency shown in current thermoelectric modules.

The domestic TCS shown in Fig. 4 is designed to be integrated with the existing boiler water supply system. The water goes into cooling plate in the main block to get pre-heated by absorbing the heat from the cold side of thermoelectric generators before enters the boiler for further heating. The hot side of the generators is maintained by the boiler waste heat, solar power and boiler-heated hot water. It includes two thermoelectric blocks, main block and parasitic block. The main block converts the heat stored in the oil tank, which absorbs solar power and boiler waste heat, to electricity and pre-heated water. Solar power and boiler waste heat are absorbed by a solar-oil heat exchanger and a gas-liquid heat exchanger respectively, which are both integrated in the oil tank of the main block. Hence, the oil tank could be heated by either solar power or boiler waste heat or the combination. However, the thermal impact between these two heat exchangers needs to be considered when they are both available. The tank size needs to be calculated according to the designed temperature level. The pre-heated water goes into the boiler for further heating. Parasitic block absorbs the heat in boiler-heated water for energy conversion and heat warm air. As a parasitic device, it doesn't significantly affect the performance of the central heating system. The generated electricity can either be used to power DC appliance like LED lights, or charge the battery. Fig. 4 shows two types of applications, wall installation in Fig. 4(a) and roof installation in Fig. 4(b), respectively. In order to obtain high operating temperature on the hot side, solar concentrator could be used to promote the temperature. Its application becomes more beneficial with the presence of other heat sources such as stoves and fireplaces. As a building block designed with a universal interface, it could be also integrated with other available heat sources in the domestic environment if there is any change.

2.3. Experimental study

2.3.1. System introduction

Experimental tests have been carried out on a bench-scale experimental prototype to investigate its performance as a building block producing electrical power and pre-heated/hot water. The schematic diagram of the test rig is shown in Fig. 5. The thermoelectric block includes 16 modules, a cold side and hot side heat exchanger. Each module, made of Bi_2Te_3, has a dimension of 40 mm × 40 mm × 3.8 mm with 127 thermocouples. The heat source is given by stable heat input from cartridge heaters. On the heat sink side, the heat is taken away by cooling water which dissipates the heat in the condenser. Part of the collected heat is converted into electricity and the rest could be used to pre-heat water for other facilities like the domestic boiler and under-floor heating. In real application, the water pump in Fig. 5 can be replaced by the existing pump in the heating system. The condenser cools down the circulated water, passively or actively, for the test by dissipating the heat to the environment; the temperature could be adjusted using fan controller. This avoids wasting large amount of tap water by circulating the water in the system although some electricity is consumed when the active cooling is required.

2.3.2. Modelling description

The energy conservative equation is given by Eq. (3):

$$Q_{input} = Q_{output} + P + Q_{loss} \tag{3}$$

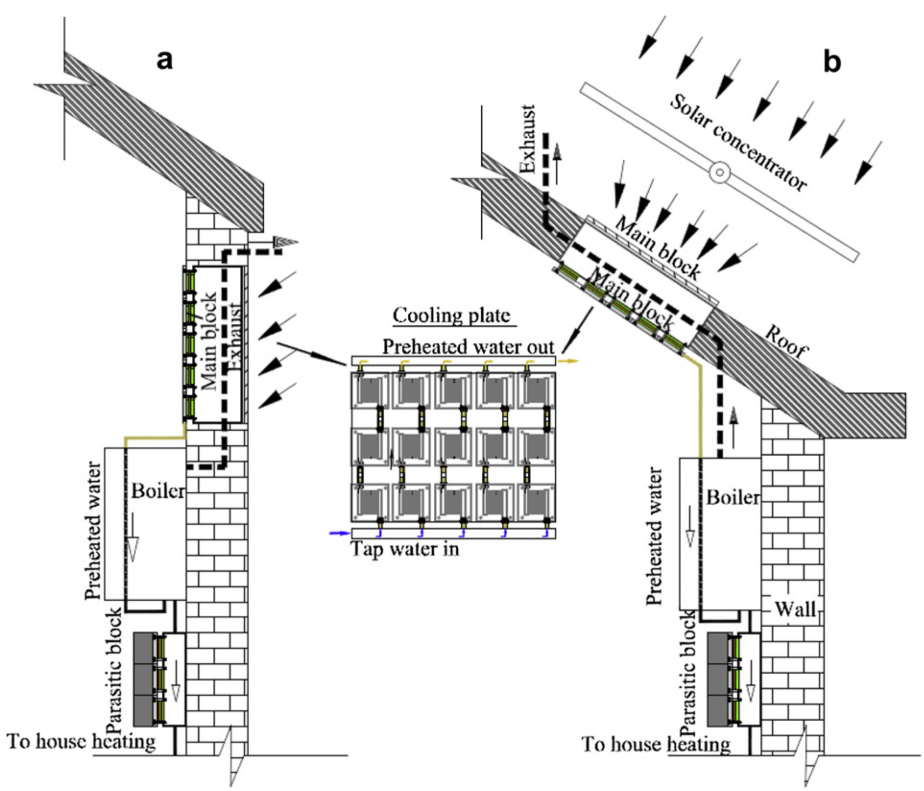

Fig. 4. Domestic application of TCS.

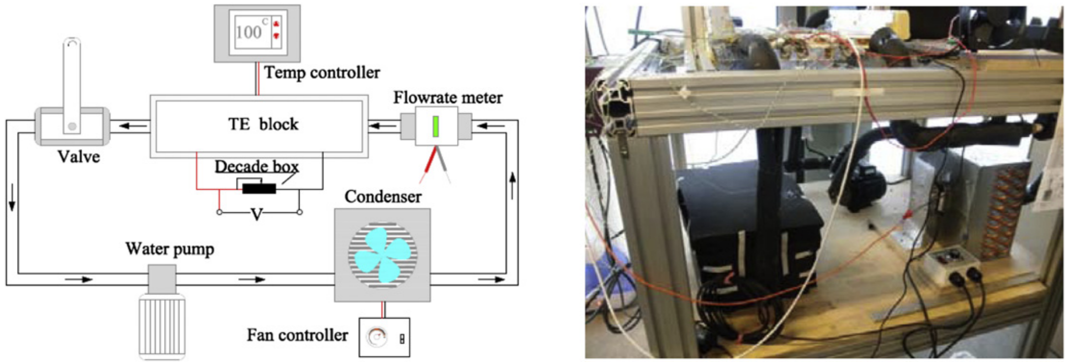

Fig. 5. Schematic diagram and photo of test rig.

Here assuming boiler waste heat and solar power as the heat source, then $Q_{input} = Q_{solar}+Q_{bw}$.

In real situation, the solar radiation varies with the weather condition and the time of the day. The boiler waste heat also varies with its operation according to the user's needs and boiler size. The influence from these two factors has not been taken into account in this study. The experimental investigations were carried out under stable heat input by using cartridge heaters. The discussion under stable heat input hopefully paves the path to the further study which covers the investigations on the availability of heat sources, boiler size and user's need under real circumstance. In Eq. (3), the capacity of heat source, which is also the heat input, equals to the sum of power output, heat output and heat loss. Assuming the temperature of heat source, heat sink, hot side, cold side and ambient are T_h, T_c, T_1, T_2 and T_a, respectively. The coolant temperatures at the inlet and outlet of heat sink and coolant flow rate are T_{inlet}, T_{outlet} and G, respectively. Therefore, power output, heat output and the heat loss can be calculated by Eq. (4), Eq. (5) and Eq. (6):

$$P = \frac{S(T_1 - T_2)^2}{R_{ex}} \tag{4}$$

P is obtained when R_{ex} matches with R_{in}.

$$Q_{output} = c\rho G(T_{outlet} - T_{inlet}) \tag{5}$$

$$Q_{loss} = \mathrm{h}A(T_h - T_a) \tag{6}$$

2.3.3. Experimental analysis

Power output and heat output have been measured to understand the system capacity and more importantly the performance characteristic under different operating conditions (the achieved temperature difference is 72 °C, the remaining part is projected according to the combination of theoretical and experimental trend). This study is to shed an insight to the potential application of TCS in the domestic sector and provide guidelines for the design and fabrication of thermoelectric building blocks. Maximum power output is defined as the power output generated when the load resistance matches with the modules resistance. This is done by adjusting the decade box.

Fig. 6 shows the outputs at different temperature difference and the corresponding power density (power output per module area). The gap between experimental and theoretical results is caused by thermal and mechanical treatments during system assembling procedures. Fig. 7 shows the conversion efficiency achieved at different temperature difference. It implies that a better performance can be achieved by a better design of heat exchangers.

The conversion efficiency shown in Fig. 7 is obtained in another set of experiment after the heat source has been modified for a higher temperature level. The rising trend of conversion efficiency is shown in Fig. 7 when the temperature difference increases. The maximum conversion efficiency (about 4%) is achieved at 130 °C. For the material used in this study-Bi_2Te_3 which is compatible with 200 °C temperature difference, higher conversion efficiency could be achieved if the temperature difference could be lifted up further.

3. Evaluation and suggestion

3.1. Energy recovery period

When considering the energy saving aspect of using thermoelectric generators, it is important that the amount of energy

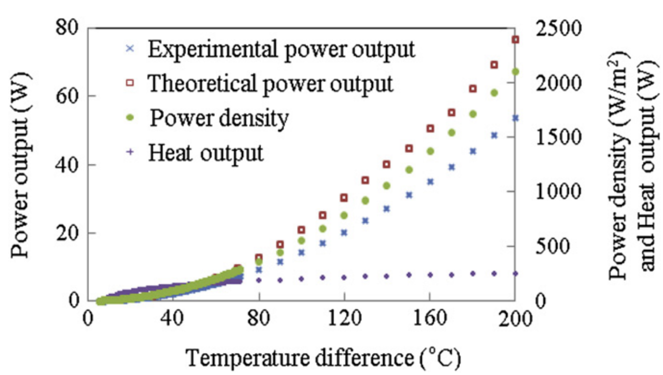

Fig. 6. System performance vs. Temperature difference.

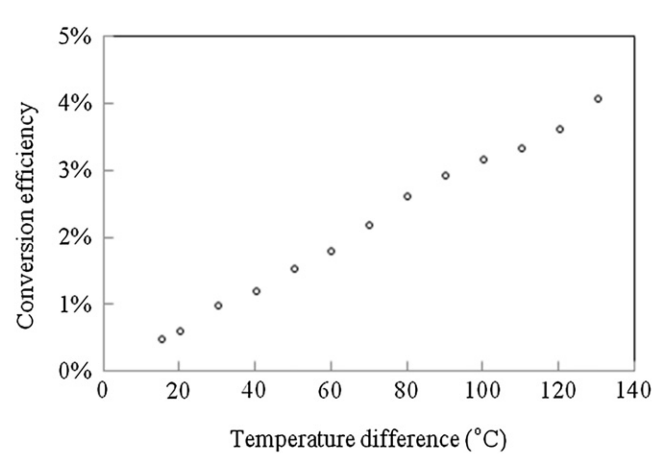

Fig. 7. Conversion efficiency vs. Temperature difference.

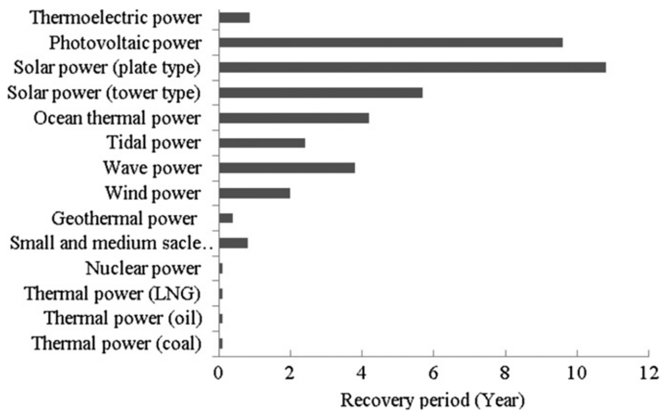

Fig. 8. Comparison of energy recovery period.

produced by the thermoelectric generators during their life time should be larger than the amount of energy used in fabrication. Fig. 8 shows energy recovery period for various methods of electrical power generation [21]. In the case of thermoelectric power generation by a Bi-Te-based module of 200 °C type, the energy recovery period is 0.85 year which shows sufficient competitiveness among other methods. As previously discussed, the annual waste heat per boiler and the yearly sum of absorbed solar power from direct solar radiation are 3076.8 kW h and 122.4 kW h/m^2, respectively. Therefore, for a residential house mounted with an 80% efficiency boiler and 10 m^{2}solar collecting panel in the UK, the annual amount of available heat could be estimated to be 4301 kW h.

Fig. 9 shows the annual cost saving and outputs of heat and electricity at different operating temperature difference based on the test rig. Using 20 mm insulation materials with thermal conductivity at 0.25W/mK (such as PTFE) and 4 mm superwool as the thermal insulation, the heat transfer coefficient can be calculated considering the natural convection and heat conducting in the insulation layer. The bigger the temperature difference, the greater electricity produced and greater cost saved. Annual cost saving is calculated according to the charge rates of a gas supplier in Table 2 and the result is shown in Fig. 9.

Heat output can be used to preheat the water for other domestic facilities like boiler to save the boiler fuel. The electricity can be either used by domestic appliance or stored in standard batter set which can be charged at the nominal voltage of 2 V, 6 V, 8 V, 12 V, 24 V and 48 V, respectively. These commercialised battery set can be configured for the DC/AC inversion. The application in this paper can power some DC appliances or charge the battery set for DC/AC inversion.

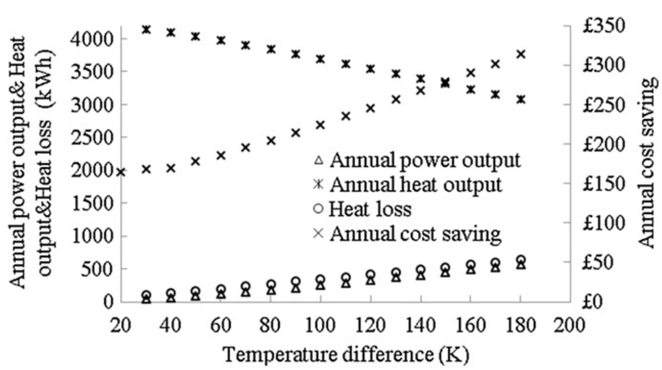

Fig. 9. Performance and cost saving of domestic TCS.

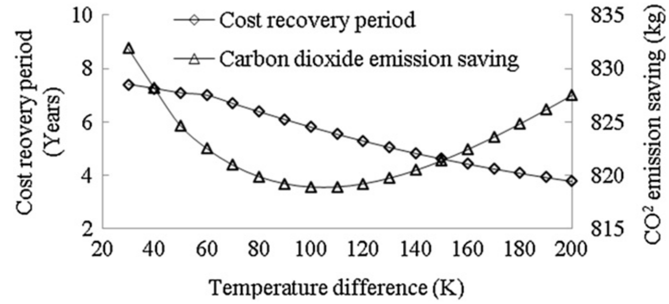

Fig. 10. Cost recovery period vs. Temperature difference.

3.2. Cost recovery period

Users are normally concerned about the time period for recovering costs when they justify the financial benefits of utilising this system. Here the cost recovery period is evaluated to provide the information for assessments. The cost for establishing this system is estimated and shown as below:

This system concept is designed to be integrated with the existing domestic hydraulic system. Assuming the cooling loop is integrated with the boiler hydraulic system, the cost recovery period can be estimated for different temperature difference, shown in Fig. 10. The period estimation is calculated based on the assumption that the annual heat of solar radiation and domestic boiler is evenly distributed throughout the year.

3.3. Economic and environmental benefits

For the common domestic thermal environment discussed previously, the achievable operating temperature difference is estimated to be 100 °C without solar concentration. Hence, the annual saving is £213 per domestic boiler user and the corresponding cost recovery period is 5.59 years. Taking the year 2009 in the UK as an example, the quantity of domestic boiler users is about 22 million, referred in Table 1. Theoretically, the possible annual cost saving for the country would be £4.7 billion assuming each boiler in the UK installs TCS. The operating temperature difference can be enlarged considerably when solar concentration is used. Environmental benefits lie in the contributions in cutting down the CO_2 emissions (shown in Fig. 10) achieved by generating electrical power and reusing thermal energy from free heat sources. The curve of CO_2 emission saving goes through a drop first (at 100 °C) and then increases as the temperature difference rises because of the different roles played by electricity and gas in cutting down CO_2 emission. A significant amount of CO_2 emission saving can be achieved both at low and high temperature difference for this system due to the cogeneration. However, the cost recovery period at high temperature difference is shorter than that at low temperature difference.

Table 1
Yearly sum of gas consumption per consumer in the UK [19].

Year	2002	2003	2004	2005	2006	2007	2008	2009
Boiler user quantity (thousands)	20,587	20,683	20,791	21,595	21,884	22,224	22,327	22,568
Gas per user (kWh)	20,118	20,111	20,496	19,020	18,241	17,614	16,906	15,384

Gas per user means the gas consumption per each boiler in the form of primary energy.

Table 2
Cost estimation (assuming the operating temperature difference is 100 °C, 64 W).

Component	Module and insulation	Conducting oil	Hot side heat exchanger	Cold side heat exchanger	Thermal interface material	Installation and operation	Total cost
Quantity	67 + 0.2m^2	1 L	1	1	5	1	£1199
Cost	£680	£2.97	£82	£87	£35	£300	

Type	First (Electricity668 kW h/Gas148 kW h)	Rest
Electricity	22.765p	9.88p
Gas	6.621p	3.05p

For electricity and gas, the rates are 22.765p and 6.621p per unit for the first 668 kW h and 148 kW h, the rest is 9.879p and 3.05p per unit, respectively.

4. Conclusion

The thermoelectric applications have been limited into niche areas due to no big breakthrough in improving figure of merit (limited to ZT = 1) for a long time. A thermoelectric cogeneration system for domestic use is proposed to suggest a way of utilising heat source maximally. The system viability has been discussed based on the availability of boiler waste heat and solar radiation. The benefit of employing thermoelectric generators for domestic applications has been evaluated on the basis of experimental studies. The results prove that this approach, capable of cutting down CO_2 emission by producing electrical power and pre-heated water simultaneously using free energy, leads us to a direction of environmentally friendly and sustainable energy generation method for residential houses. For the current thermoelectric materials with a low figure of merit, it can be a partial supplement for the domestic power generation. However, it shows a great potential to transform to a major domestic power generation method with short cost recovery period when the commercial module with a higher figure of merit was available. Nevertheless, for successfully translating the laboratory work into commercial applications, continued efforts need to be made on the optimum heat exchanger designs, thermal and mechanical treatments and onsite integrations.

Acknowledgements

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Nomenclature

A	exterior surface area of heat source m^2
G	coolant flow rate m^3/s
h	heat transfer coefficient W/m^{2}K
P	maximum power output W
Q_{bw}	available boiler waste heat W
Q_{input}	heat input W
Q_{loss}	system heat loss to the ambient environment W
Q_{output}	heat output W
Q_{solar}	available solar power W
R_{ex}	external electrical resistance Ω
R_{in}	module electrical resistance Ω
S	Seebeck coefficient V/K
T	absolute temperature °C
T_a	ambient temperature °C
T_c	heat sink temperature °C
T_h	heat source temperature °C
$\overline{T}$	average operating temperature °C
T_1	module hot side temperature °C
T_2	module cold side temperature °C
T_{outlet}	outlet water temperature °C
T_{inlet}	inlet water temperature °C
ZT	dimensionless figure of merit
Z	figure of merit K^{-1}

Greek symbols

η	conversion efficiency
λ	thermal conductivity W/m K
ρ	water density kg/m^3
σ	electrical conductivity S/m
ΔT	temperature difference across thermoelectric module K

References

[1] Department of Energy and Climate Change, A National Statistics Publication: UK Energy in Brief available at (2010) :, http://www.decc.gov.uk/assets/decc/statistics/publications.
[2] J.C. Bass, N.B. Elsner, F.A. Leavitt, Performance of the 1 kW Thermoelectric Generator for Diesel Engines 13th International Conference on Thermoelectrics, Kansas City, NO, American Institute of Physics (1995) (New York).
[3] K. Matsubara, M. Matsuura, Thermoelectric Applications to Vehicles (Chapter 52), , In: Thermoelectric Handbook, Macro to Nano, CRC Press, 2005.
[4] M.K. Ewert, Terrestrial and Aerospace Solar Heat Pump Development: Past, Present and Future, ASME paper at Solar '98, Albuquerque, NM (1998).
[5] D.M. Rowe, United States Thermoelectric Activities in Space, in: Proceedings VIII Int Conf on Thermoelectric Energy Conversion, Nancy, France, 10–13 July 1989, pp. 133–142.
[6] G. Bennett, Space applications (Chapter 41), in: D.M. Rowe (Ed.), CRC Handbook of Thermoelectrics, CRC Press, 2005.
[7] Department of Trade and Industry, Energy Consumption in the United Kingdom, National statistics Available at (July 2002) :, http://webarchive.nationalarchives.gov.uk.
[8] U.S. Department of Energy, Energy Loss Reduction And Recovery In Industrial Energy Systems. Available at: http://www1.eere.energy.gov.
[9] D.M. Rowe, Thermoelectric conversion of waste heat from redundant oil wells, in: Proceedings Mediterranean Petroleum Conf (1992), pp. pp.556–563.
[10] T. Kajikawa, I. Makoto Ito, I. Katsube, E. Shibuya, Development of thermoelectric power generation utilising heat of combustible solid waste, in: B. Mathiprakasam (Ed.), Proc. of the 13th Int. Conf. on Thermoelectrics, Kansas City Mo (1994), pp. 314–318.
[11] T. Kajikawa, Thermoelectric power generation systems recovering heat from combustible solid waste in Japan, in: Proc. of the 15th Int. Conf. on Thermoelectrics, Pasadena, USA (1996), pp. 343–351.
[12] A. Killander, J. Bass, A stove-top generator for cold areas, in: Proc. of the 15th Int. Conf. on Thermoelectrics, Pasadena, USA (1996), pp. 390–393.
[13] D. Mastbergen, B. Wilson, S. Joshi. Generating light from stoves using a thermoelectric generator. Available from: http://www.vrac.iastate.edu/ethos/files/ethos2005/pdf/mastbergen_paper.pdf.
[14] R.Y. Nuwayhid, D.M. Rowe, G. Min, Low cost stove-top thermoelectric generator for regions with unreliable electricity supply, Renewable Energy 28 (2003) 205–222.
[15] K. Qiu, A.C.S. Hayden, A natural-gas-fired thermoelectric power generation system, Journal of Electronic Materials 38 (7) (2009) 1315–1319.
[16] D.M. Rowe, Thermoelectric waste heat recovery as a renewable energy source, Int. J. Innov. Energy Syst. Power 1 (2006) 13–23.
[17] M. Suri, T.A. Huld, E. Dunlop, H.A. Ossenbrink, Potential of solar electricity generation in the European Union member states and candidate countries, Solar Energy 81 (2007) 1295–1305.
[18] Boiler efficiency database. http://www.sedbuk.com/.
[19] Department of Energy and Climate Change, A National statistics Publication: energy Trends. Available from: http://www.decc.gov.uk/assets/decc/statistics/publications/trends/1511-trendsmarch11.pdf.
[20] T. Caillat, Fleurial, J.P. and Borshchevsky, A., Development of High Efficiency Thermoelectric Generators using advanced Thermoelectric Materials, Albuquerque, New Mexico, USA.
[21] S. Sano, H. Mizukami, H. Kaibe, Development of high-efficiency thermoelectric power generation system, Komatsu Technical Report Vol. 49 (No. 152) (2003).